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Effects of air pollution on grapevines

by

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Introduction

This review will include discussions of the major studies on the effects of air pollutants on foliar symptoms, growth and development, accumulation of airborne ecotoxicants in and on the grapevine, and yield and quality of the fruits. Reviews have been published on the subject of general air pollution effects on grapes (ANONYMOUS 1976,

VIESSMAN *et al.* 1982), airborne fluorides (F) (GREENHALGH *et al.* 1980, State Pollution Control Commission 1981), and pollutants produced by combustion of fossil fuels (MUSSELMAN *et al.* 1980).

Historical background

Viticulture in the eastern United States includes 4 groups of grapes. The first group, and by far the largest, are the native American hybrids, with 'Concord' the dominant member. An outstanding hybrid from the N.Y. State Agricultural Experiment Station at Geneva, NY, is 'Cayuga White'. The second are the French hybrids, represented by 'Baco noir' (Baco No. 1), 'Seyval' (Seyve Villard 12-375), 'Aurore' (Seibel 5279), 'Chancellor' (Seibel 7053), 'Marechal Foch' (Kuhlmann 188-2). The third group is comprised of a few cultivars of *Vitis vinifera* including some of the wine grapes of Europe and California. And the fourth group includes cultivars of *V. rotundifolia,* the Muscadine grapes (such as Scuppernong) grown in the southeastern part of the U.S. The grape industry in the western part of the U.S. is dominated by cultivars of *V. vinifera.*

Problems in the evaluation of air pollution effects on the grapevine

Although the response of the grapevine to airborne phytotoxicants has many characteristics in common with the response of other crops, there are also a number of differences that may modify the interpretation of effects in the field or under experimental conditions. Unquestionably the most important characteristic of the grapevine with respect to its response to air pollution is that it is a deciduous perennial plant and may have the capacity for a high rate of productivity over many decades. The quantity and quality of fully-expanded leaves, especially the basal leaves of the shoots, are crucial to growth and development of the vine. Their development and protection are a primary objective of trellising because they constitute the major source of sugar production that provides the energy for vine and fruit growth and development (JORDAN *et al.* undated). Because the flower cluster primordia are produced during the year preceding cropping, research cannot be confined to a single year. The response to an airborne phytotoxicant, therefore, may represent the cumulative effects on the vine over a number of years. Other characteristics of the plant and its methods of culture may be important considerations under experimental conditions. Vines are generally planted in rows and are often supported by trellises of different configurations depending upon local preferences and other characteristics of the cultivars being grown. Because some vines are very robust, as in the case of 'Concord', the most commonly used enclosures for experimental air pollutant exposures are generally inadequate and cannot accomodate more than a single vine (MUSSELMAN, KENDER and CROWE 1978), although as many as 2 of the less robust vinifera vines have been used in each chamber (MURRAY 1983). In some cases, 'chamber effects' have been detected by long-term enclosure (MUSSELMAN, KENDER and CROWE 1978, MURRAY 1983). (An excellent discussion of the characteristics of the open-top chamber to study effects of air pollution on grapes has been published [WEINSTOCK *et al.* 1982].) Furthermore, under favorable growth conditions, the roots of the vine will spread over an area beyond the boundary of the enclosure and may result in differences in soil-water relationships inside and outside the chamber. In order to reduce crowding, increase the number of vines per chamber, and improve overall growth conditions, large chambers of different designs have been constructed and are presently being used or tested·(BREWER and ASHCROFT 1983, MANDL *et al.,* personal

comm.). Another approach to help resolve some of the problems created by field chambers, has been the use of open-field exposures (CANTUEL 1980, BONTE and CANTUEL 1983); but other problems are created by this approach, such as the lack of exclusion of existing pollutants in the ambient air, a suitable distribution system, and sufficient spatial monitoring of pollution additions.

Symptomatology

Ozone

Oxidant stipple of grape leaves was first reported in the summer of 1954. The injury described was due to ozone (O_3) present in the oxidant complex, although oxidized organics, such as peroxyacetylnitrate (PAN), can cause silvering, bronzing, and necrosis of lower leaf surfaces (MIDDLETON et al. 1955). The following symptoms are often referred to as either "oxidant" or "O_3" stipple. Symptoms appear as small, brown to black, discrete lesions that are confined to cells of the upper leaf surface. The lesions are restricted to the palisade cells in areas of the leaf bounded by the smallest veins. The symptoms may be distinguished from other grape disorders such as K deficiency (black leaf), by their stippled appearance. The primary lesions vary in size from 0.1—0.5 mm in diameter; large lesions of up to 2 mm in diameter may be produced by coalescence. The typical stippled appearance is due to aggregates of the primary lesions. With severe oxidant injury, yellowing, bronzing, premature senescence, and abscission may occur (RICHARDS et al. 1958, 1959, LEDBETTER et al. 1959, SHAULIS et al. 1972, KENDER and SHAULIS 1973, KENDER and MUSSELMAN 1976, MUSSELMAN, KENDER and CROWE 1978, MUSSELMAN et al. 1980, ORMROD 1979, SHERTZ et al. 1980, MUSSELMAN 1980). The importance of minimizing and ameliorating O_3 stipple in normal management of New York vineyards has been described (JORDAN et al., undated). Older leaves and the oldest parts of younger leaves are most vulnerable to oxidant stipple.

In most cultivars, the necrotic stipple lesions remain small. They may become larger in 'Blue Elba' ('Blau Elbe'?) and 'Grenache', and are often accompanied by anthocyanosis in 'NY Muscat' (BANKS and ORMROD, undated).

The O_3-induced lesions occur characteristically in the palisade layer of the leaf. Cells at the periphery of the lesion often have enlarged starch grains in the chloroplast. Cells near the center of the lesions are usually most severely affected with browning of protoplasts and starch accumulation. Where lesions have coalesced, the upper epidermal cells over the damaged palisade cells are often collapsed (SHAULIS et al. 1972). Similar histological symptoms were described by LEDBETTER et al. (1959) for avocado, which was studied along with grape as one of several species that developed stipple symptoms when fumigated with O_3.

Sulfur dioxide

In *V. labruscana* cv. 'Fredonia', young leaves exposed to SO_2 show greyish-brown lesions at the margin, tip, or in intercostal areas. In older leaves, injury appears as a dark greyish-green color changing to greyish-brown in the intercostal areas of the leaf. Veins remain green. Severely afflicted leaves often abscise. Middle-aged leaves are most sensitive (KATZ et al. 1939, FUJIWARA 1970, FUJIWARA 1975).

Ozone/sulfur dioxide

Investigations of O_3/SO_2 interactions with grapes, other than visual or correlative observations, appear to be limited to the study of SHERTZ et al. (1980). When the gases

were combined, injury symptoms of each gas were produced in the susceptible 'Ives' or tolerant 'Delaware' cultivars. In a brief discussion of the combined effects of O_3 and SO_2 on crops (ANONYMOUS 1966), injury to grapes is mentioned, but it is not clear whether the statement is directed to injury produced by the individual or combined gases.

Hydrogen fluoride

Injury to grapevines by airborne F was first described in detail by Prof. HOLLAND in Maurienne, France in 1906—1907 (BOSSAVY 1966), and later in greater detail by FAES (1921). In the time since publications of these early reports, industrial emissions of F-containing compounds have been reported to injure grapevines in many geographic areas of the world. Among these are some of the most important grape growing regions: the Lagarina Valley near Trentino, Italy (COLOMBINI et al. 1969); the province of Reggio Emilia, near Sassuolo (FOGLIANI 1976); the Rhône Valley (Valais) of Switzerland, (BOVAY and BOLAY 1965; BOLAY et al. 1969); the region of Lacq-Nogueres, France (VIEL and DE CORMIS 1965, DE CORMIS et al. 1978); the Hunter Valley in New South Wales, Australia (State Pollution Control Committee 1981); the Swan Valley of W. Australia (WILSON and PLUES-FOSTER 1976, 1978); and the area near San Bernadino, Calif. (BREWER et al. 1956, 1957). Many other reports have been published that describe injury to grapevines in industrial areas (e.g., RIPPEL 1970, QUELLMALZ and OELSCHLAEGER 1971, POLELLI 1978) or from accidental spills of HF (QUARONI et al. 1979).

The first symptom of F injury is the appearance of a grey-green color at the margin of the relatively young leaf. The affected area is supple, but ultimately becomes brown or reddish-brown in color and is often separated from the green portion of the lamina by a darker brown, reddish-brown, or purple band near the interface between green and necrotic tissue. A thin band of chlorotic tissue may occur as a transition zone between the dark band and the green area. Dark concentric bands also may appear in the necrotic areas due to earlier exposures of F (BREWER et al. 1956, BREWER et al. 1957, RICHARDS et al. 1958, BOLAY and BOVAY 1965 b, BOSSAVY 1966, HOPP 1966, COX and JONES 1981, GREENHALGH and BROWN 1981, HORNE et al. 1981). HORNE et al. (1981) and COX and JONES (1981) reported that old leaves were affected first but this may have been a result of the time necessary to accumulate sufficient F to exhibit symptoms. QUARONI et al. (1979) found greatest injury in the young leaves, with greatest accumulation in older leaves. This is the generally-held view.

Some differences in the appearance and quality of foliar lesions have been reported. In V. vinifera cv. 'Traminer', the first sympton to appear was tip necrosis, whereas in 'Gordo', it was chlorosis. 'Traminer' foliage never exhibited chlorosis, and 'Gordo' foliage became necrotic only after the degree of chlorosis was severe (DOLEY 1981).

COX and JONES (1981) reported that berries exposed to high atmospheric F concentration were discolored to a pinkish hue.

Factors affecting susceptibility

Ozone, sulfur dioxide, carbon black

According to RICHARDS et al. (1958) leaf stipple lesions in the field occurred early in the growing season on relatively young, but fully-expanded leaves of the 16 varieties studied. The youngest, terminal, developing leaves were not affected. Lesions continued to form throughout the season with new injury occurring on young, expanded

leaves and a progressive accumulation of stipple on older, maturing leaves. The
researchers concluded that the 'inciting agent' (ozone) affects only developing and
maturing leaves and is present throughout the growing season. SHERTZ et al. (1980)
found that in 'Ives' and 'Delaware', the greatest amount of foliar injury from exposure
to O_3 or SO_2 was in the fully-expanded leaves at nodes 2, 3, and 4 (Fig. 1). Symptoms
appeared in the field on mature leaves near the base of the shoot on the O_3-susceptible
cultivar 'Ives' about 3—4 weeks before they appeared on the somewhat more tolerant
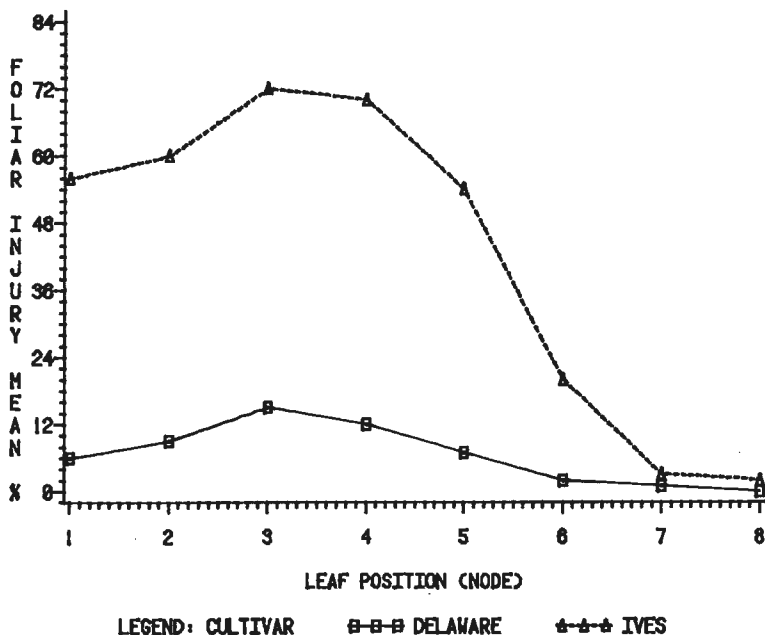cultivar 'Concord'.

Fig. 1: Effect of leaf position on foliar susceptibility of two grape cultivars to fumigations with SO_2
and/or O_3 (from SHERTZ et al. 1980).

In their review on the effects of pollutants that result from combustion of fossil
fuels, MUSSELMAN et al. (1980) also point out that basal leaves of shoots are most suscep-
tible to O_3 injury, causing premature senescence and abscission. Because these leaves
are important for shoot maturity, fruit production, and fruit composition, their loss
may have deleterious effects on productivity. The same researchers have also summa-
rized the conditions of the plant or the environment that affect the response of the gra-
pevine to foliar injury, growth, and yield (Fig. 2) (KENDER and SHAULIS 1976, SHAULIS
1977, MUSSELMAN 1980, MUSSELMAN et al. 1980). Among the most important cultural fac-
tors that reduce foliar injury on 'Concord' vines are use of own-rooted vines, low soil
moisture, and a high level of nitrogen in the leaves.
    Inheritance of tolerance to O_3 injury has been the subject of studies by MUSSEL-
MAN, POOL, MELIOUS and KENDER (1978). Mature progeny from reciprocal crosses
between the O_3-susceptible 'Ives' and the O_3-tolerant 'Chancellor' were examined over 2
growing seasons to determine patterns of inheritance to O_3 susceptibility. Parental
vines and a backcross population of 'Chancellor' with 'Ives' were also examined. Prog-
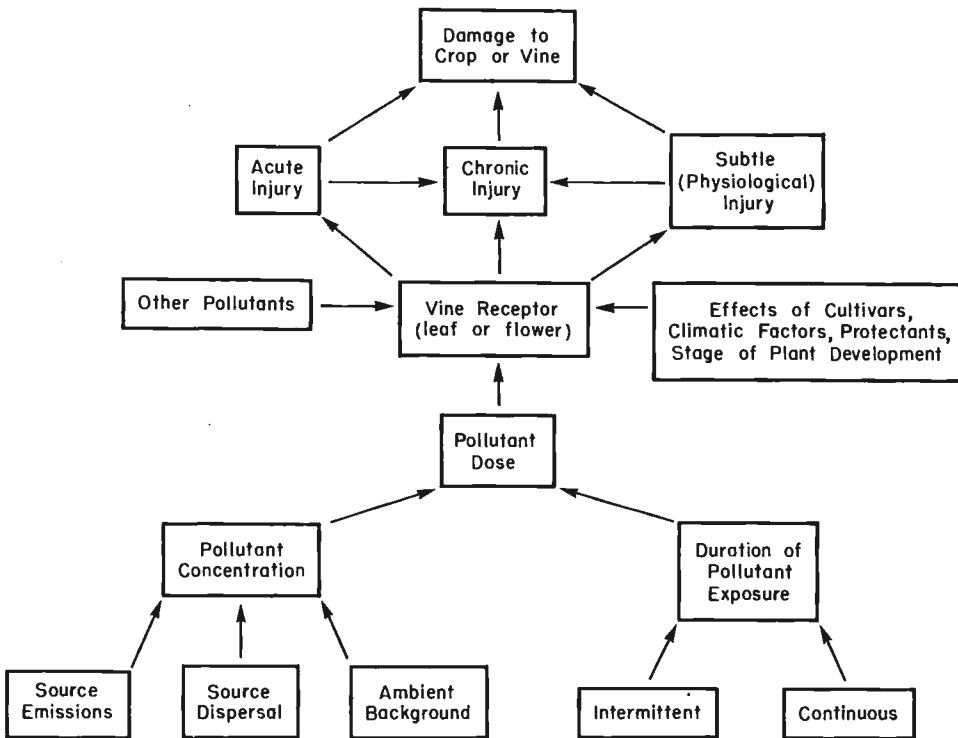
Fig. 2: Factors that control effects of air pollution on grapevines (modified from MUSSELMAN *et al.* 1980).

eny from all crosses varied widely in their susceptibility to O_3. But the data suggested that inheritance of susceptibility may be maternal with most progeny resembling 'Ives' when it was the female parent.

FUJIWARA (1970) found that as the SO_2 concentration increased over a 7-week period (control, 0.065, 0.13, and 0.26 ppm = 0, 170, 340, 680 µg m^{-3}), leaf abscission in 'Fredonia' vines began earlier and progressed at a greater rate (Fig. 3). When 'Fredonia' vines were exposed to 0.26 ppm SO_2 at different times of the growing season, suscepti-bility to SO_2 gradually increased from summer to fall. The importance of light in mediating uptake and injury to grapes was demonstrated by ISHIKAWA (1972). Leaves exhibited injury when exposed continuously to 0.26 ppm SO_2 for 24 h, but injury symp-toms required 14 days of only daylight exposure to reach the same threshold.

In the highly industrialized Copsa Mica zone of Rumania, the damaging effects of sulfur-containing effluents was enhanced by the presence of carbon black. This was due presumably to the capacity of carbon black to absorb and retain SO_2 and the authors concluded that there was a SO_2/carbon black interaction (IONESCU *et al.* 1971).

Hydrogen fluoride

Great variation in the susceptibility of some *V. vinifera* cultivars was found at dif-ferent stages of growth, while the degree of susceptibility in others was relatively uni-form. For example, the spring flush of growth in 'Pedro Ximenes' (spelled differently in
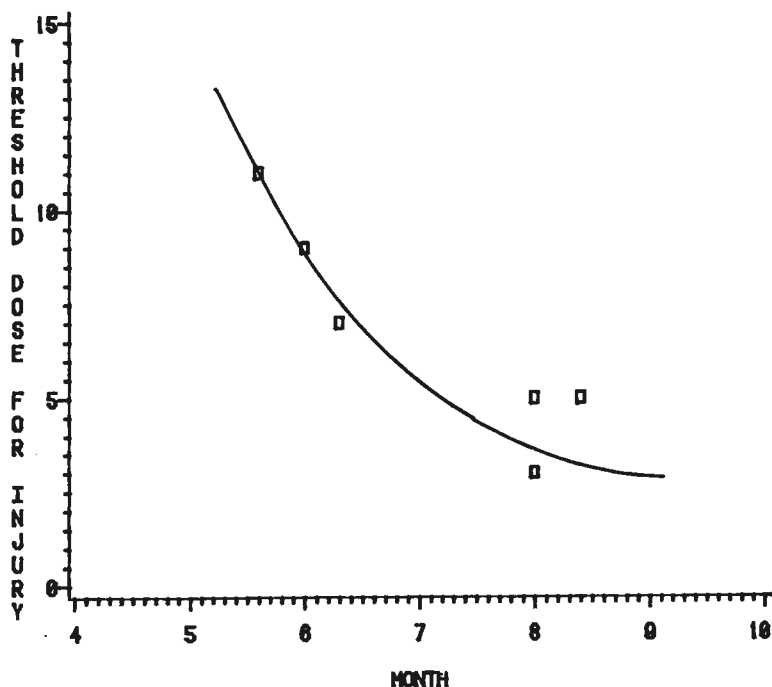
Fig. 3: Seasonal susceptibility of 'Fredonia' grapevine to injury by SO_2 (from Fujiwara 1970).

Australia) was very tolerant, but leaves in early summer, late summer, and early fall were susceptible to HF injury. By contrast 'Concord' was found to be uniformly tolerant throughout the growing season (Brewer et al. 1956).

Relative susceptibility to air pollutants

The importance of factors other than the concentration or the dose of pollutant that determine the vulnerability of grapevines to air pollutants should be obvious from the following discussion. It also demonstrates some of the problems inherent in establishing air quality criteria by accepting without question any or all results published in the literature.

Ozone and photochemical oxidants

A number of cultivars and selections grown in the field at the NY State Agriculture Experiment Station in Geneva, NY were classified according to O_3 susceptibility (KENDER and CARPENTER 1974). The degree of O_3 stipple was given for American cultivars (Table 1), French hybrids (Table 2), and selections used in breeding programs (Table 3). The smaller-leaved American cultivars, such as 'Ives' which are exceptionally susceptible to O_3, also have a higher stomatal resistance than more tolerant cultivars. This suggests that non-stomatal factors are important in the O_3 susceptibility of 'Ives' (ROSEN et al. 1978 a, 1978 b).

Table 1

Percent oxidant-induced stipple on grape cultivars in New York State and Ontario, Canada · 1973[1])
(from KENDER and CARPENTER 1974)

Very Mild 0—5 %	Mild 6—25 %	Moderate 26—50 %	Considerable 51—75 %	Severe 76—100 %
Delaware[2])	Niagara	N.Y. Muscat	Concord[2])	Veeport[2])
Himrod	Agawam	Catawba[2])	Lady Patricia	Bath
Iona	Athens	Norwood	Wayne	Elvira
Seneca	Lake Emerald	Schuyler	Erie	Noored
Dutchess[2])	Golden Muscat	Van Buren		Brighton
Canada Muskat[2])	Naples	Alden		Keuka
Hanover	Steuben	Concord		Fredonia
Kendaia	Vinered	Seedless		Eclipse
	Yates			Kensington
	Buffalo			Urbana
	Interlaken			Ripley
	Seedless			Mills
	Salem			Clinton
	Vincent[2])			Sheridan
	McCampbell			Portland
	Cayuga White[2])			C. 3309[2])
	Alwood			Ives[2])
	Romulus			

[1]) Listed in increasing order of susceptibility in each column.
[2]) Rated in both 1972 and 1973.

The most susceptible cultivars in southwestern Ontario to oxidant stipple were found to be 'Veeport', 'Marechal Foch', 'De Chaunac', and 'Baco noir' with 40—70 % injury on leaves. 'Himrod', 'Delaware', 'Dutchess', and 'Niagara' were relatively tolerant (ORMROD, undated report). These results agree with the report of KENDER and CARPENTER (1974).

As early as 1958, oxidant stipple had become a common feature of the grape-growing areas of California. 'Carignane', 'Grenache', 'Palomino', and 'Pedro Ximenes' appeared to be more susceptible than 'Burger', 'Thompson Seedless' (=Sultanina), and 'Zinfandel'. Symptoms were also present in V. californica and V. girdiana. In chambers, the percent of the total leaf surface affected from exposures to unfiltered ambient air was 'Carignane', 89 %, 'Palomino', 62 %, 'Blue Elba' 43 %, and 'Thompson Seedless', 9 % (RICHARDS et al. 1958, 1959).

Exposure to O_3 at 0.3 ppm (590 µg m^{-3}) for 6 h on 4 successive days gave the following susceptibility rankings for 5 French hybrids and one American hybrid: 'Baco noir' ≈ 'Marechal Foch' > 'De Chaunac' ≈ 'New York Muscat' > 'Villard noir' > 'Le Commandant'. The differences in degree of susceptibility were not great, however, and the presence of 0.6 ppm SO_2 (1,570 µg m^{-3}) for the same exposure periods had no effect on the response of the plants to O_3. Exposure to O_3 induced a red coloration to leaves of 'New York Muscat', while the other cultivars exhibited yellow-brown stippling (BANKS and ORMROD, undated report). A concentration of 0.10 ppm O_3 (196 µg m^{-3}) for 8 h had no effect on 'Zing', 'Tokay', or 'Concord' foliage, but stipple was produced when these

cultivars were exposed for 8 h at 0.30—1.0 ppm O_3 (590—1960 µg m^{-3}) (LEDBETTER *at al.* 1959). TRESHOW (1970) reported that 4 h at 0.25 ppm (490 µg m^{-3}) produced mild stippling on 'Concord'.

Hydrogen   fluoride

Grapes, especially some *V. vinifera* cultivars, are very sensitive to airborne F. *V. vinifera* cv. 'Roter Gutedel' was found to be very susceptible to F and susceptible to SO_2 (DÄSSLER *et al.* 1972), and many European cultivars were classified with apricot, one of the most susceptible plants to F (BOLAY and BOVAY 1965 a, 1965 b). Other researchers (THOMAS and ALTHER 1966, TRESHOW and PACK 1970) listed 'some European varieties' as susceptible (Class 2) and 'Concord' as intermediate (Class 4) (of a total of 6 classes), while others (POLELLI 1977, 1978) classified *V. vinifera* as 'extremely sensitive' to HF and 'sensitive to SO_2'. *V. vinifera* 'Barbera' was reported to be more susceptible to HF than cv. 'Lambrusco' by POLELLI (1977).

Table 2

Percent oxidant-induced stipple on French hybrid grape cultivars in New York State and Ontario, Canada · 1973[1]) (from KENDER and CARPENTER 1974)

Very Mild 0—5 %	Mild 6—25 %	Moderate 26—50 %
LeCommandant (BS 2862)	Seibel 10868	Rosette (S. 1000)[2])
Joannes Seyve 12-428	Verdelet (S. 9110)	Aurore (S. 5279)[2])
Landot 4511	Chelois (S. 10878)[2])	Cascade (S. 13053)[2])
Colobel (S. 8357)	Humbert 3	Rougeon (S. 5898)[2])
Seyve-Villard 172	Bertille-Seyve 2846	Foch[2])
Seyve-Villard 23-512	Vignoles (Ravat 51)[2])	Leon Millot[2])
Seibel 10076	Rayon d'Or (S. 4986)	Joannes Seyve 26-627
	Chancellor (S. 7053)	Baco Noir
	Seibel 14117	Chambourcin (JS 26-205)
	Seyve-Villard 18-307	Raat Blanc (Ravat 6)
	Valarien (SV 23-410)	Seyve-Villard 12-203
	Seyval (SV 5-276)[2])	
	Seibel 8229	
	LeGeneral (BS-5563)	
	Joannes Seyve 23-416	
	Landal (Landot 244)	
	Tehere Dore (Ravat 578)	
	Seibel 7136	
	Seibel 13047	
	Villard Blanc (SV 12-375)	
	Villard Noir (SV 18-315)	
	DeChaunac (S. 9549)[2])	
	Seibel 13666	

[1]) Listed in increasing order of susceptibility in each column. No French hybrids were classified in the 'considerable' or 'severe' injury categories.
[2]) Rated in both 1972 and 1973.

Table 3

Percent oxidant stipple of certain selections from the breeding programs of the N.Y. State Agricultural Experiment Station at Geneva, N.Y., and the Vineland Station, Ontario, Canada · 1973[1]) (from KENDER and CARPENTER 1974)

Very Mild 0—5 %	Mild 6—25 %	Moderate 26—50 %	Considerable 51—75 %	Severe 76—100 %
Vidal 256	N.Y. 31987	N.Y. 30454	V. 37014	N.Y. 45916
V. 54077	V. 50061	N.Y. 35814	N.Y. 32037	N.Y. 34840
N.Y. 14528	N.Y. 45198	N.Y. 45625	N.Y. 34981	N.Y. 36037
N.Y. 25542	N.Y. 17324	N.Y. 34824[2])	N.Y. 49404	
N.Y. 34338[2])	N.Y. 44968	N.Y. 29805[2])	V 35081	
N.Y. 36268	N.Y. 33472	N.Y. 45010		
N.Y. 36297	N.Y. 34988[2])			
N.Y. 36661	N.Y. 36125[2])			
N.Y. 36806	N.Y. 34803[2])			
N.Y. 38167	N.Y. 14302			
N.Y. 42355				
N.Y. 42603				
N.Y. 44897				
N.Y. 32042				
N.Y. 34791				

[1]) Listed in increasing order of susceptibility in each column.
[2]) Rated in both 1972 and 1973.

BREWER *at al.* (1956) also classified commercial grape cultivars with respect to F susceptibility: 'Mission', 'Mataro', and 'Burger' were highly susceptible, 'Palomino', 'Zinfandel', and 'Alicante' were moderately susceptible, and 'Blue Elba', 'Carignane', and 'Grenache' were moderately tolerant to airborne F. Not only was there a wide difference in susceptibility between the cultivars, but the degree of susceptibility varied with the season (or stage of development). In greenhouse fumigations, for example, there were wide differences in the degree of susceptibility. 'Colombard' was ranked as very susceptible and 'Pedro Ximenes' as very tolerant at the time of the spring flush. But in early fall, the susceptibility of 'Colombard' decreased while that of 'Pedro Ximenes' increased.

DOLEY (1981) classified grape susceptibility according to the time elapsed ('critical response time' [Dc]) between the initiation of fumigation at a given concentration and the occurrence of the lowest foliar F concentration associated with foliar lesions (Fc) and a given duration of exposure per day (Tf). Thus,

$$Dc = (Fc - b)/kATf$$

where b is the initial concentration in the leaves, A is the ambient concentration, and k is the rate of F uptake by the leaf.

Data for 3 cultivars indicated that 'Chardonnay' was the most susceptible cultivar. Injury to 'Gordo' required 4 times more exposure, and injury to 'Traminer' required 5 times more exposure; the relationships were assumed to be constant over a range of concentrations of airborne F from 0.01—0.75 ppb, v/v (0.008—0.60 µg m^{-3}). It is doubtful that injury in the grape is a linear function with time and concentration, and assump-

tions of the number of days required to produce visible injury in *V. vinifera* cv. 'Chardonnay', 'Gordo', and 'Traminer' appear to be unreasonably high.

GREENHALGH and BROWN (1982b) classified 14 cultivars grown in Australia to F injury according to the number of injured leaves per plant and the number of injured leaves per meter of shoot growth (Table 4). The most important white and red cultivars, 'Semillon' and 'Shiraz' (='Syrah'), ranked high in susceptibility depending upon the method of evaluation.

Wild grape is equally susceptible to HF and SO_2 according to ZIMMERMAN and HITCHCOCK (1956), but exposures used to determine this relationship were high (50 ppb HF, v/v = 40 µg m^{-3} or 500 ppb SO_2 = 1310 µg m^{-3}). Cultivars of *V. vinifera* were classed as susceptible. In an attempt to relate stomatal frequency to susceptibility to these gases, 13 cultivars of grapes were examined. The number of stomata per mm^2 on the abaxial surface of the leaf ranged from 116—268, and these extremes were represented by 'Salvador' (= 'Seibel 128') (268 per mm^2) and 'Muscat of Alexandria' (= 'Gordo') (116 per mm^2), both relatively tolerant to HF. Hence, no relationship was identified between susceptibility and number of stomata in grapes.

Grape cultivars grown in western Australia were ranked into 2 F susceptibility classes, which were called 'severe' and 'mildly affected', and which we might consider to be 'relatively susceptible' and 'relatively tolerant'. In the relatively susceptible cate-

Table 4

Classification of 14 cultivars into sensitivity classes to HF fumigations according to 2 criteria (from GREENHALGH and BROWN 1982 b)

Sensitivity	Ranking of cultivar according to			
	number of injured leaves per plant		number of injured leaves per metre of shoot	
High	Black Muscat	(R)[1]	Semillon	(W)
	Flora	(W)[1]	Flora	(W)
	Shiraz	(R)	Black Muscat	(R)
Medium	Palomino	(W)	Rhine Riesling	(W)
	Barbera	(R)	Chardonnay	(W)
	Rhine Riesling	(W)	Traminer	(W)
	Isabella	(R)	Palomino	(W)
	Cabernet		Shiraz	(R)
	Sauvignon	(R)	Barbera	(R)
	Semillon	(W)	Malbec	(R)
			Cabernet Sauvignon	(R)
			Isabella	(R)
Low	Chardonnay	(W)	Blanquette	(W)
	Blanquette	(W)	Zinfandel	(R)
	Traminer	(W)		
	Zinfandel	(R)		
	Malbec	(R)		

[1]) R = red/black, W = white.

gory, 'Black Malaga', 'Red Emperor', 'Ohanez', 'Pedro Ximenez' (= 'San Pedro'), and 'Semillon', and in the relatively tolerant group 'Grenache', 'Shiraz', 'Cabernet Sauvignon', and 'Chenin blanc' were listed (Cox and JONES 1981).

Sulfur dioxide

The relative susceptibility of several cultivars of grape to SO_2 has also been compared (FUJIWARA 1970). Of the species tested, 'Fredonia' was the most susceptible, followed by 'Delaware' = 'Kyoho' > 'Neomuscat' > 'Kyogei' > 'Koshu'.

VIEL and DE CORMIS (1965) reported that 'Petit Manseng' had an SO_2 injury threshold of 2.5 ppm (6550 µg m^{-3}), while 'Tannat' was 15 ppm (39,300 µg m^{-3}). This method of expressing degrees of susceptibility is useful only for comparative purposes because there was no indication of time or total dose, and concentrations were excessively high.

Of 191 species of plants tested with SO_2, V. vinifera cv. 'Roter Gutedel' was found to rank 22nd and was classified as 'susceptible' (RANFT and DÄSSLER 1970).

Exposure of several cultivars to 0.6 ppm SO_2 (1570 µg m^{-3}) for 6 h a day on 4 successive days resulted in essentially no injury to 'Baco noir', 'Marechal Foch', 'De Chaunac', 'New York Muscat', 'Villard noir', or 'Le Commandant' (BANKS and ORMROD, undated report).

Dose, rate of uptake, and accumulation

Hydrogen fluoride

The relationship between foliar accumulation of F and the threshold for foliar injury has been a subject of controversy for many years. ADAMS et al. (1957) were among the first researchers to recognize that 'dose' (the product of time and concentration), which they called the 'exposure factor', was a more accurate criterion of susceptibility to F than was accumulation. Experiments with V. vinifera, however, were not good examples to support their hypothesis. Plants exposed to 5 ppb HF, w/w (6 µg m^{-3})[1]) and a dose of 252 ppb-h (300 µg m^{-3}-h) accumulated 138 ppm F (µg g^{-1}, dry weight) by the first sign of foliar injury. At 10 ppb, w/w (12 µg m^{-3}) the dose was 344 ppb-h (413 µg m^{-3}-h) and F accumulation was 122 ppm. In the dark at 5 ppb, w/w (6 µg m^{-3}) the dose was 522 ppb-h (626 µg m^{-3}-h) and accumulation was 84 ppm. It is clear from these results that grapes (and other species of plants) tend to develop foliar injury at lower levels of F accumulated in darkness than in light, and absorption proceeds at about ⅓ the rate in darkness as in light. The correlation coefficient of dose vs. foliar F content was not significant for exposure in the light. Other researchers have shown that uptake in leaves generally is greater in the light than in the dark, and in grape DOLEY (1982) reported that the most rapid uptake occurred between 0800 and 1200 hours.

GREENHALGH et al. (1981, 1982 a, 1982 b), based principally upon data derived from glasshouse fumigations in southeastern Australia, has suggested that injury is induced in leaves of 'Shiraz' and 'Semillon' when F accumulation reaches 30 ppm and at an atmospheric concentration of ca. 0.12 ppb, v/v (ca. 0.1 µg F m^{-3}), a dose of 180—216 ppb-h (150—180 µg m^{-3}-h), or at a concentration of 0.26 ppb, v/v (0.22 µg m^{-3}) for 47 d, a dose of 310 ppm-h (250 µg m^{-3}-h). Background concentrations in control

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[1]) HF concentration expressed as weight per weight instead of the usual volume per volume.

leaves were generally 10—12 ppm. Other investigators (Cox and Jones 1981, Horne *et al.* 1981) report the threshold for foliar injury to be less than 20 ppm in foliage of 'Pedro Ximenez' (also called 'Pedro' and 'San Pedro') grown in the field. On the basis of their results, both research groups have recommended that an air quality standard for grape-growing regions of Australia should not exceed 0.12 ppb, v/v (0.1 µg m⁻³) ambient average for a growing season. According to the New South Wales State Pollution Control Commission (1981 a, 1981 b, 1982), however, concentrations in grape tissues in the Hunter Valley as high as 48 ppm have produced minor injury on only rare occasions and have questioned the validity of a standard as low as 0.12 ppb, v/v (0.1 µg m⁻³) for a growing season average (State Pollution Control Commission 1981 a). In the Rhône Valley of Switzerland (the Valais) healthy leaves of *V. vinifera* have been reported to contain from 50 ppm up to about 105 ppm. In necrotic leaves, none contained 25 ppm or less, but 40 % of the total leaves analyzed had F contents between 26 and 105 ppm (Bovay 1954, 1958, Bolay and Bovay 1965 b, Bovay and Bolay 1965). Doley (1984) reported that older leaves of 'Chardonnay' and 'Gordo' could accumulate up to 1000 ppm F without exhibiting injury. Under field conditions, Murray (1983) apparently found no injury on foliage of 'Shiraz' at 55 ppm and Brewer *et al.* (1956) found none on foliage of 'Emperor', 'Concord', or 'Pedro Ximenes' at 150—250 ppm.

Leece *et al.* (1982) and Leece and Scheltema (1983) provide a good discussion of the problems associated with determining 'threshold' or 'critical values' that relate F accumulation and the appearance of foliar injury. Symptoms resembling injury induced by airborne F may be due to other stress agents. An unusually low F content may influence the fitting of curves and lead to an estimate of a low threshold value. This may have accounted for the differences in estimates of the threshold values for foliar injury of 20 ppm and 25 ppm between Cox and Jones (1981) and a reevaluation of the same data by Horne *et al.* (1981). If one eliminates all questionable values for threshold concentrations that have appeared in the literature, there is reasonably compelling evidence that slight F injury can be induced in the most sensitive cultivars in the field at 35—40 ppm. The threshold for injury under field conditions in Italy near an HF spill was also about 35—40 ppm (Quaroni *et al.* 1979). Leece *et al.* (1982) also point out that there is no physiological basis for the concept of a discrete threshold value, i.e., that necrosis or other foliar injury will always appear at a certain F content in the leaf. Not only is concentration related to the threshold for injury, but so are factors such as the distribution of F within the leaf, its physiologic and metabolic activity, and the many climatic and edaphic factors that determine sensitivity to F (Weinstein 1977). Doley (1984) has provided excellent data on the relationship between F uptake by grapes and its relation to wind speed and boundary layer conductance. About 84 % of the variation between treatments in the rate of F accumulation could be explained by changes in wind speed. There was no significant improvement in describing the rate of F accumulation by inclusion of boundary layer conductance.

A poor relationship has been reported to exist between the F content and percent necrosis of foliage. In individual leaves of 'Chardonnay', there was a considerable amount of variability, e.g., one leaf was injured at less than 20 ppm while there were many uninjured leaves with more than 100 ppm F (Doley 1982). Doley concluded that at an ambient concentration of 0.24 ppb, v/v (0.2 µg m⁻³), there would be one chance in 40 that an injury index of 10 (10 % injury on 10 % of the leaves, or 1 % injury on all leaves) would be reached within 44 days, and an even chance that the index would be reached within 80 days.

Generally, the accumulation of F in grape leaves is more or less progressive with the length of time of exposure (Cantuel 1980, Doley 1982, 1984). Accumulation of F in young leaves of 'Chardonnay' was found to be a linear function of dose and did not dif-

fer significantly between leaves exposed at 0.48, 1.1, or 1.7 ppb, v/v (0.4, 0.9, or 1.4 µg m^{-3}). The regression for F accumulation was F = 11.291 + 0.094 AT (DOLEY 1982). No evidence of saturation was found for F accumulation in 'Gordo', 'Traminer', and 'Chardonnay' up to 400 µg g^{-1} (DOLEY 1984). Others (HORNE *et al.* 1981) found that accumulation of F was described by a quadratic rather than a linear function in 'Pedro Ximenez', or by a third-degree polynomial model (LEECE and SCHELTEMA, 1983). These results emphasize the inconsistencies found in the literature between research groups using different methods of exposure, cultivars, statistical models, analytical methods, and innumerable other differences in methodology.

There is a considerable amount of evidence from sampling of grape leaves exposed to airborne F compounds in the field that F accumulation from plant-to-plant is extremely variable and a poor predictor of foliar injury. In one area of the Rhône Valley of Switzerland, BOLAY *et al.* (1969) found that the F content of leaves varied between 32 and 620 ppm. Among possible explanations for the randomness of these data are (1) analytical error perhaps related to lower reliability of F analyses in the 1950s, (2) lack of uniform sampling (including the proportion of leaves of different ages in a sample), and (3) removal of F from the exterior or interior of the leaf by precipitation or other forms of weathering. The grape berry and other parts of the vine do not accumulate F internally. The organ of accumulation of F in the grapevine (and in other species as well) is the leaf, and there is little or no translocation to other organs of the plant (DE CORMIS *et al.* 1978). Therefore the grape berry is generally low in F content except where surface contamination occurs. Nevertheless, the values cited by DE CORMIS *et al.* (1978) are nearly 10 times greater than those reported by BREWER *et al.* (1957) in areas of F pollution.

MORENO MARTIN *et al.* (1971, 1972) examined the F contents of leaves, musts (crushed grapes), and wines of many grape cultivars in Tarragona and Barcelona regions of Spain. All samples were found to contain low background concentrations of F.

Although F is not normally accumulated in the grapevine from soilborne F, there are certain notable exceptions. When grapevines (and other fruits) are fertilized with certain boron-containing products that are manufactured by reaction of a strong acid with a mixture of rock phosphate (naturally high in F), K salts, and borax, there is a potentiation in the uptake and accumulation of F in the foliage that often results in foliar injury. Since the fertilizer has a high F content, it is believed that accumulation results from absorption in the form of fluoroborate (BF$_4$). There is no accumulation of F in the fruits from the fertilizer (BOLAY *et al.* 1969, BOVAY 1969, BOVAY *et al.* 1969, COLLET 1969, COLLET *et al.* 1969, BOLAY *et al.* 1971).

Sulfur dioxide

FUJIWARA (1970) studied the increase in S content of leaves of 'Koshu' and 'Fredonia' grape cultivars exposed to SO$_2$. In general 'Fredonia', the more SO$_2$-sensitive cultivar, accumulated more S in leaves than 'Koshu' and at a greater rate. But the use of foliar analysis of S as an indicator of SO$_2$ pollution is not always useful because of the high endogenous S content of plants generally.

Heavy metals

Pb was found to accumulate in grape berries of 'Traminer' and 'Pinot Grigio' (= 'Pinot gris') exposed to automobile exhaust fumes along a road in northeastern Italy (MARLETTA *et al.* 1973, FAVRETTO *et al.* 1975). The concentration diminished parabolically with the logarithm of the distance from the source. The values found 13 m from the

center of the roadway were ca. 0.8—1.0 ppm (μg g^{-1}) dry weight, as compared with ca.
0.3—0.4 ppm dry weight in a normal area. Simple washing with water had no signifi-
cant effect on the contamination because of the hydrophobic nature of the skin of the
berry, but all the Pb could be accounted for in the skin. Lead accumulation 50 m from
the road was negligible (MARLETTA et. al. 1973). In a study of 'Traminer' grapes in the
same area, the deposition of Pb was studied in grape berries, leaves, and soil. The con-
centration of Pb in these materials was 0.43, 6.7, and 16.2 ppm. Within experimental
error, the deposition on equal surface areas of leaves or berries was about the same
(FAVRETTO et al. 1975).

Pb in grape berries and wine was determined from vineyards located along road-
ways and near factories in Germany. Results of the study showed that (1) berries near
roadways contained up to 2—4 times as much Pb as those 25—50 m away, (2) wines
made from berries grown near a factory that manufactured Pb and Cd-containing pig-
ments often had markedly elevated Pb contents as compared with wines from other
areas, (3) the content of Pb and Cd in the must (crushed grapes) decreased with dis-
tance from the factory, and (4) Pb was found mainly on the surface of the berry while
Cd penetrated into the interior of the fruit (MACK and BERG 1972, MACK 1975).

The heavy metal content of 'Delaware' grapes was studied by students from 55 pri-
mary schools in Sakai City, Japan under the direction of faculty of Osaka University.
Leaves and berries were collected from potted grapevines distributed throughout the
area and analyzed at Osaka University, for a variety of heavy metals. Leaves were often
high in Zn, Ni, Cu, Pb, and Cd; berries in Ni and Cu (NAKAGAWA et al. 1973).

Growth and yield

Ozone (and other photochemical oxidants)

Growth characteristics of 12-year-old 'Concord' grapevines grown in open-top
chambers supplied with charcoal-filtered air or nonfiltered ambient air were compared
with vines grown in outside ambient air (MUSSELMAN et al. 1978). The experiment was
carried out over a 4-year period (1973—1976). Leaves of vines grown in charcoal-fil-
tered chambers (except for 1973) had less oxidant stipple than in nonfiltered chambers
or the ambient air. Soluble solids of grape berries were higher in charcoal-filtered
chambers than the other treatments, but the results were statistically significant only
when data from the 4 years of experimentation were combined. Despite the lower level
of soluble solids in treatments containing ambient air, all grapes met the grape proces-
sor's minimum standards for soluble solids. Regardless of treatment all vines grown in
open-top chambers had lower pruning weights than those grown in ambient air over
the 4-year period. At the end of the experiment, vines grown in chambers were smaller
than those outside, despite an effort at the beginning of the experiment to select vines
as uniform as possible. The overall effect of enclosure was a significant reduction in
the extent of shoot maturation. Mean fruit set over the 4-year period was not signifi-
cantly different between treatments. The weights of berries, clusters, and fruit per vine
were not affected by treatment. The smaller vines in the charcoal-filtered air yielded as
much fruit as larger vines in ambient air. Premature abscission and senescence of
leaves were markedly reduced in charcoal-filtered and nonfiltered chambers. The
authors concluded that there was a significant chamber effect on overall vine growth
that may have masked important effects of O$_3$, and they caution researchers in the use
of open-top chambers for long-term experiments with perennial crops.

THOMPSON *et al.* (1969) and THOMPSON and KATS (1970) studied the response of 'Zinfandel' grapes to photochemical smog near Cucamonga, Calif. in 1968—1969. In addition to the predominant phytotoxic pollutant, O_3, the air contained peroxyacylnitrates (PANs) and NO_2. The experiment consisted of 12 plots, each with 4 'Zinfandel' grape vines covered by closed-top plastic greenhouses. The 12 chambers were separated into 2 groups of 6 chambers that were exposed to ambient air or to charcoal-filtered air. In 1968, after 14 weeks, the vines in charcoal-filtered air were greener, as verified by chlorophyll analyses. After about 16 weeks, the grapes were harvested. In charcoal-filtered air, the fresh weight per berry, sugar content of juice, weight of prunings, and yield of grapes per vine were much higher than in nonfiltered ambient air treatments. In the second season (1969), the differences between charcoal-filtered and nonfiltered air continued, and there was a remarkable difference in the yield of grapes per vine. This effect was attributed to damage of the 1969 inflorescences during their development in 1968.

More recently, BREWER and ASHCROFT (1983) completed a 4-year field investigation on the effects of ambient photochemical oxidants on yield of 'Thompson Seedless' grapes in the central San Joaquin Valley, California. 8 large rectangular open-top chambers were used to provide 4 charcoal-filtered air and 4 nonfiltered ambient air treatments in the 1979—1982 growing seasons (mid-April to mid-October). Exposure to ambient air significantly reduced pruning weights in 1980, 1981, 1982, and 1983, with a 4-year average reduction of about 12 %.

No effects were found in fruit production in 1979, the first year of the study, since inflorescence primordia are formed during the previous year. The 1980 crop was lost due to severe mildew and bunch rot infestations. In 1981, exposure to ambient air reduced bunch set and fruit yields by 17 % and 28 %, respectively, and in 1982, by 11 % and 17 %, respectively. In general, 1982 was a much higher yielding year than 1981, and the authors suggested that the effects of ambient oxidants had a greater effect in years of low yield than years of high yield. The greater reduction in fruit yield than in the number of fruit bunches suggested that size of the bunch was a more sensitive measure of effect than the number of bunches.

Effects of ambient pollution on fruit quality were less distinct than on other characteristics. Berry size and percent acid were not affected in the two years measured. There was a small but significant reduction in the sugar content of berries in 1981 and in the overall mean for the three years in which measurements were made.

The authors conclude that ambient photochemical oxidants have a significant impact on yield and, to a lesser degree, on quality of 'Thompson Seedless' grapes. As in previous research by the authors with cotton, yield reduction was due principally to reduced fruit set.

Sulfur dioxide

'Fredonia' and 'Delaware' cultivars grown in pots were exposed to control, 0.065, 0.13, and 0.25 ppm SO_2 (0, 170, 340, and 680 µg m^{-3}, respectively) for 159 days from May 23 to October 29 in controlled environment chambers (FUJIWARA 1970). Observations on growth and yield made on May 14 of the next year confirmed the greater susceptibility of 'Fredonia' over 'Delaware' to SO_2 exposure (Tables 5 and 6). In 'Fredonia', exposure to 0.065 ppm reduced shoot length, and fresh and dry weights of shoots by nearly 40 %, and the number of flower clusters by about 65 %; at 0.13 ppm, shoot length and fresh and dry weights of shoots were reduced about 60 % and cluster formation by 80 %; and at 0.26 ppm the plants were killed (Table 5). In the more tolerant 'Delaware' exposure at 0.065 ppm had no effect on shoot length, fresh and dry weights of shoots, or cluster

Table 5

Influence of SO_2 exposure of the preceding year on new shoot growth and cluster formation of 'Fredonia' grape (from FUJIWARA 1970)

Exposure-treatment[1])	Total length of shoot	Fresh weight	Dry weight	No. of cluster
Control	198.5	63.2	12.1	10.5
0.065 ppm	118.0	37.0	6.6	3.6
0.13 ppm	87.3	28.0	4.7	2.0
0.26 ppm	—[2])	—	—	—

[1]) Exposure periods were 159 days from May 23 to Oct. 29, 1976.
[2]) —: no sprouting.

formation; at 0.13 ppm, cluster formation was reduced by 40 %, but other characteristics of the vine were unaffected; and at 0.26 ppm, shoot length and fresh and dry weights of shoots were reduced about 50 %, and cluster formation was completely inhibited (Table 6) (FUJIWARA 1970).

In New York State, a field study was conducted to determine the long term effects of SO_2 from power plant emissions on growth, development, yield, and soluble solids of 'Concord' grapevines and berries. The experiment was carried out in open-top field chambers from June to mid-October in 1977, 1978, and 1979. Vines were exposed to concentrations of SO_2 that were predicted to occur from a proposed power plant to be built in that area. The SO_2 was added to chambers supplied with ambient air. The power plant simulation fumigations were to be at 0.12 and 0.20 ppm SO_2 (310 and 520 µg m^{-3}, respectively) 2—8 h per day, during 32 days throughout the season. 19 exposures were to be at 0.12 ppm for 4 h. 2 fumigations were scheduled at 0.20 ppm for 3 h and 0.20 ppm for 2 h, and 2 for 8 h at 0.12 ppm. The actual concentrations were somewhat lower than intended during 1977 and 1978. Results from experiments over a 3-year period indicated that there were no effects on vine size, wood maturity, degree of chlorosis, or yield. In 1977 or 1978 there were no symptoms of SO_2 injury, but a small amount of necrosis occured in 1979. Perhaps the most significant finding was that the presence of SO_2 resulted in a marked increase in the degree of O_3-induced stipple on leaves, suggesting that the presence of SO_2 enhanced the degree of O_3-induced stipple. Soluble solids were significantly reduced in 1977, but not in 1978 or 1979 (MUSSELMAN 1980).

Table 6

Influence of SO_2 exposure of the preceding year on new shoot growth and cluster formation of 'Delaware' grape (from FUJIWARA 1970)

Exposure-treatment[1])	Total length of shoot	Fresh weight	Dry weight	No. of cluster
Control	304.4	68.1	13.8	21.0
0.065 ppm	302.0	74.3	15.2	20.0
0.13 ppm	304.2	67.4	13.4	8.0
0.26 ppm	174.7	35.2	7.3	0

[1]) As shown in Table 5.

In a second experiment conducted over the same 3-year period, vines of 'Concord' were exposed to 0.10 ppm SO_2 (260 µg m^{-3}) for 12 h each day from June until mid-October in charcoal-filtered open-top field chambers. This exposure regime caused marked reductions in soluble solids, vine size, and wood maturity, and was associated with SO_2-induced necrosis and chlorosis of leaves. Leaves were chlorotic on the vines the year following fumigations and, because of the reduction in vine size, yield was also reduced (MUSSELMAN 1980).

Sulfur dioxide/ozone

SHERTZ et al. (1980) studied the effects of O_3, SO_2, and their combinations on some growth characteristics of 'Ives', an O_3-susceptible cultivar, and on 'Delaware', an O_3-tolerant cultivar. Potted plants were exposed in a 2×3 factorial design for each cultivar at control, 0.4, and 0.8 ppm O_3 (0, 750 and 1570 µg m^{-3}) or SO_2 (0, 1050 and 2100 µg m^{-3}) in all combinations and for a 4-h period. (The authors have made an obvious error in their publication in expressing pollutant concentration 3 orders of magnitude too high.) SO_2 injury was apparent several h after treatment, but O_3 injury required 3 days for maximum expression of symptoms. When introduced alone, not only did O_3 and SO_2 induce typical symptoms of the respective gases, but even when introduced together, symptoms were relative to the amount of each gas present. As expected, both pollutants, alone or combined, produced more injury on 'Ives' than 'Delaware'. There were no apparent differences in foliar injury when plants were exposed to 0.40 ppm of SO_2 or O_3, but the authors have stated that at 0.80 ppm, 'Ives' was more sensitive to O_3 and 'Delaware' to SO_2. This comparison is not shown in the data. The discussion appears to have many inconsistencies in statements regarding foliar injury and the statistical analysis seems to be inappropriate to determine synergism or antagonism. Mature leaves were found to be most susceptible to O_3 and/or SO_2. Shoot growth was inhibited more in 'Ives' than in 'Delaware'.

EDMONDS et al. (1982) conducted a 3-year study from 1978—1980 on the potential impact of simulated SO_2 emissions from a proposed 1700 MW coal-burning power plant in northwest New York State on growth, development, yield, and quality of 'Concord' vines. A total of 13 open-top field chambers were used, each enclosing a single vine. An ambient plot of 50 vines was also used. Treatments within chambers were allotted as follows: 4 chambers received ambient air, 4 received charcoal-filtered air, and 5 were exposed to SO_2. The SO_2 simulation regime was administered as a step function for 2—8 h, with each step lasting one h. SO_2 concentrations ranged from 0.02 to 0.16 ppm (50—420 µg m^{-3}) and they were applied generally during mid-day on an average of 4 days per month from May (bud break) to October (post-harvest).

Biological variables were analyzed by parametric and nonparametric techniques. Significant differences were found between vines inside or outside of chambers, but no significant responses could be detected in growth and development (measured as periderm formation), pruning weight, number of fruit clusters, number of clusters per shoot, and number of seeds per berry; leaf injury estimated as percent of chlorotic or necrotic leaf area; or yield as measured by the number, retention, weight, or sugar content of berries.

Hydrogen fluoride

Perhaps the most extensive field experiments on the effects of airborne F on grape yield were conducted in 1980—1982 (CANTUEL 1980, BONTE and CANTUEL 1983), and are apparently still being continued. Open-field fumigations with HF were conducted during the period of 1980—1982 using V. vinifera cv. 'Petit Manseng'. HF was intro-

duced between the rows of vines through a system of 'diffuseurs'. 78 feet of vines were exposed to concentrations of 0.18—0.36 ppb, v/v (0.15—0.30 µg m^{-3}) through 3 vegetative cycles from bud burst to harvest. 2 control areas were also used. In 1982, the maximum amount of foliar injury for the first 10 leaves was 3.2 % of the total surface, but yield was reduced by 9.9 % and 15.5 % of the yields for the two control plots, respectively. The authors have concluded that after 3 years of exposure, airborne F at the concentrations applied may reduce vine fertility, but they also state that it is premature to make conclusions from the available data because of the many other factors that influence yield of the vines.

In glasshouse fumigation experiments with potted plants, GREENHALGH and BROWN (1982 a, b) studied effects of long-term exposures of HF on several characteristics of growth of *V. vinifera* cv. 'Shiraz'. After exposure to a mean HF concentration of 0.10 ppb, v/v (0.08 µg m^{-3}) for 91 d, there were no significant effects on shoot length, number of nodes, or the plastochron index. Foliar F concentrations were 10.1 ± 4.9 ppm (µg g^{-1}, dry weight) in controls and 29.01 ± 6.9 ppm in fumigated plants. In 'Semillon', no effects on shoot growth, leaf area, dry weight of foliage (including rates of photosynthesis and respiration) were found in leaves where marginal necrosis was apparent. Stomatal resistance varied inversely with the F dose, being lowest in older leaves of the highest F treatment (GREENHALGH and BROWN 1982 a, b).

In Germany (HOPP 1966), emissions of F from a brick factory caused severe injury to an unidentified cultivar(s) of grapes, and the degree of injury depended upon distance and direction from the source. Within 200—400 m of the factory, injury was sufficiently severe to induce leaf abscission. The F content of leaves in the so-called control areas was 22—24 ppm (about 2 times the currently-accepted background concentration, suggesting that the sites were still in a somewhat contaminated area). In affected areas, leaf concentrations were reported to be about 150—250 ppm. Interestingly, in a zone nearest the factory the leaves contained less F than in more distant areas. One reason for this phenomenon suggested by the author was that the presence of necrotic tissue reduced absorption and translocation within the leaf, thus decreasing the absorption of solubilized particulate F. No quantitative data on yield or growth were recorded except the unsubstantiated observation that the sugar content of the berries was extremely low and ripening was delayed.

Emissions of F from 2 brick factories have caused problems with grape culture in the Swan Valley of W. Austrialia. In *V. vinifera* cv. 'Pedro Ximenez' ('Pedro', 'San Pedro'), vines with foliar injury had fewer branches per vine and fewer grapes per bunch. Unfortunately, no data or other direct evidence was presented (HORNE et al. 1981).

Severe injury to *V. vinifera* cv. 'Muscat Hamburg' was reported in China near a 'HF-polluted area'. Injured vines exhibited weak growth, slender and weak shoots, markedly shortened internodes, small and chlorotic leaves, poorly developed buds, premature defoliation, and small fruit clusters with fewer and smaller berries bitter to the taste. In general, when the HF concentration of the atmosphere was 8.6—40.0 ppb, v/v (7.1—31.8 µg m^{-3}), reduction in yield was 37—66 %, which translated to about 1000—1500 catties per mu (7500—11250 kg ha^{-1}) (LIU and FENG 1981).

MURRAY (1983, 1984 a, 1984 b, State Pollution Control Commission 1983) recently conducted a 2-year field study in the Hunter Valley of southeastern Australia with *V. vinifera* cv. 'Shiraz'. 6 open-top chambers were used, each enclosing the same two vines used throughout the 2-year study. Treatments consisted of duplicate chambers receiving ambient air with 0.12 ppb, v/v added (0.1 µg F m^{-3}, low F treatment), ambient air with 0.25 ppb, v/v added (0.2 µg F m^{-3}, high F treatment), air passed through alkali-treated filters (control), and ambient field conditions (no chamber). In the first year,

fumigations were carried out over a period of 64 d. The actual F concentrations in the atmosphere were reported as 0.34 ± 0.23 ppb, v/v (0.28 ± 0.19 µg m⁻³, high F), 0.22 ± 0.14 ppb, v/v (0.17 ± 0.11 µg m⁻³, low F), and 0.16 ± 0.11 ppb, v/v (0.13 ± 0.09 µg m⁻³, ambient F). The F concentration in the filtered control was ca. 0.06 ppb, v/v (0.05 µg m⁻³). Fluoride concentrations in fumigated leaves increased rapidly to 85 and 55 ppm (µg g⁻¹, dry weight) in the high and low F treatments, respectively, and then remained constant. Leaves grown in the ambient air increased from 9 to 20 ppm during the experimental period, but leaves from vines in the filtered chambers remained relatively constant at less than 11 ppm F. At harvest, there were no differences in clusters per vine, grapes per vine, weight of grapes per vine, or water content per grape, total fruit acids, or potential alcohol (°Be). Differences were found between 'low' and 'high' F chambers and the outside ambient plots, but there were few differences between the two treatments and the charcoal-filtered control with respect to several characteristics of yield (Table 7). In the second year, vines were exposed for 189 d. The mean concentrations of airborne F were 0.27 ± 0.13 µg m⁻³ (high F), 0.17 ± 0.07 µg m⁻³ (low F), 0.07 ± 0.03 µg m⁻³ in the control chambers, and 0.08 ± 0.03 µg m⁻³ in the ambient air. The maximum leaf F concentrations were lower in the second year: 62, 27, and 9 ppm (µg g⁻¹), respectively, compared with 15 ppm in leaves of vines grown in the ambient air. Despite the lower amount of F accumulated in the second year, necrotic lesions appeared on vines in the high F chambers after ca. 83 d and in the low F chambers after ca. 99 d of continuous fumigation. In both years, the F content of berries was low but was significantly higher than nonfumigated treatments. Peduncles accumulated relatively high amounts of F, but the total amount and the rate of F accumulation

Table 7

Grape bunch characteristics at harvest in response to fluoride treatment (from MURRAY 1983, 1984 a, 1984 b)

Treatment	Bunch wet wt. (g)	No. grapes per bunch	Grape yield per vine (kg)		F content of leaves at harvest (µg g⁻¹ dry wt.)
			Wet	Dry	
1981—1982					
Control chambers	51.5 ab[1])	47.0 ab	1.92 a	0.47 a	<11
Ambient	56.6 a	50.5 a	2.47 a	0.54 a	20
Low F chambers	50.0 b	43.4 b	1.86 a	0.42 a	55
High F chambers	48.2 b	43.7 b	2.03 a	0.46 a	85
1982—1983[2])					
Control chambers	34.0	32.0	1.05	0.31	9
Ambient[3])	—	—	—	—	15
Low F chambers	35.4	35.0	1.14	0.36	27
High F chambers	38.6	34.0	1.27	0.35	62

[1]) Mean separation in columns by Duncan's multiple range test. 5 % level.
[2]) No effects found in 1982—1983 experiment.
[3]) Values not reported.

was much greater in the first than the second year (MURRAY 1984 a, 1984 b, State Pollution Control Commission 1983). As was the case in the first year, no significant differences were found in characteristics of yield and quality. The author concluded that the foliage of 'Shiraz' grapevines is sensitive to low concentrations of HF over extended exposure periods. An examination of the results also demonstrates that the effects of enclosure were greater than those of F exposure alone (see MUSSELMAN, KENDER and CROWE 1978). The State Pollution Control Commission (1982, 1983) has taken a conservative view and indicated that results with 'Shiraz' may not apply to other cultivars or to other sets of climatic conditions.

Acid rain

FORSLINE et al. (1983) have published the only experiments relating to acid rain and grape culture. Rain values as low as pH 3.3 have been reported in the Finger Lakes region of New York, where the experiments were conducted. Simulated rain was formulated to contain the background ions found over a 26-week period in the National Atmospheric Deposition Program station in Aurora, NY in 1979 (where the mean pH was 4.7). Simulated acid rain solutions at pH 2.5, 3.5, 4.5, and 5.5 were made up to contain H_2SO_4-HNO_3 in a 2:1 ratio.

In 1980 experiments, 'Concord' grapes were sprayed 3 times one week before or at anthesis using simulated rain of pH 2.5, 3.5, 4.5, 5.5, or no spray. Necrotic lesions were evident at pH 2.5 and 3.5. More foliar injury occurred when sprays were applied at anthesis than before. At harvest, plants that had been sprayed at pH 2.5 at anthesis produced fruits with lower soluble solids and the effect was associated with the degree of necrosis of the leaf opposite the grape cluster. The incidence of chlorosis was also higher at pH 2.5. The degree or extent of O_3 stipple was not influenced by treatment.

In 1981 experiments, lesion formation occurred infrequently at pH values above 2.75 as compared with pH 3.5 in 1980. Obviously, climatic and edaphic factors can alter the threshold for injury. In a comparison test of 8 cultivars treated prior to anthesis, only 'Aurore', 'De Chaunac', 'Ives', and 'Catawba' had reduced pollen germination due to acid rain treatment. The lowest rates of pollen germination were correlated with the most acidic solution (pH 2.75) in 'Aurore', 'De Chaunac', and 'Catawba'. Of these cultivars, only 'De Chaunac' exhibited a corresponding reduction in fruit set, number of seeds per berry, and berry weight at pH 2.75; and only 'De Chaunac' and 'Ives' had lower soluble solids at that pH value. Acid rain had no effect on oxidant stipple in these tests but natural oxidant stipple was believed to be responsible for the reduced content of soluble solids. In another test, there was a significant decrease in oxidant stipple in 'Concord' foliage sprayed with simulated rain at pH 2.75 or 3.25 as compared with controls receiving only ambient rainfall.

Although the results of these experiments are interesting, little information pertinent to the effects of acid rain on grapes has been provided and, as the authors state, more research is needed on the effects of acid rain and its possible interaction with O_3, temperature, relative humidity, physiological age of the leaf, and other environmental variables.

In a status report on the effects of air pollutants on crops, DE CORMIS and VIEL (1969) reported values for rain as low as pH 4, but they doubted that this level of acidity would affect grape culture.

Miscellaneous pollutants

Emissions of SO_2, HCl, Cl_2, F_2, and HF in an industrial region of Germany have been reported to damage or retard maturation of grape fruits. The fruit is injured by

uptake of these pollutants into the leaves and directly through the wax coating of the berry in some cases. The presence of a number of pollutants, including 'smoke', mineral oil vapors, asphalt, and tar has been reported to adversely affect the taste of berries. Dust and soot deposits on the plants slow the ripening process and impair the taste. Pb can be introduced into wine from contaminated berries grown near highways. One possible (but unproven) beneficial effect has been noted: Ca deposits from cement works may produce a better wine by neutralizing acidity (WEISS 1971).

Pb in grape berries and wine produced from the berries was determined from vineyards located along roadways and near factories in Germany. Results of the study showed that (1) berries near roadways contained up to 2—4 times as much Pb as those 25—50 m away, (2) wines made from berries grown near a factory that manufactured Pb and Pb-containing pigments often had markedly elevated Pb contents as compared with wines from other areas, (3) content of Pb and Cd in the must (crushed grapes) decreased with distance from the factory, and (4) Pb was found mainly on the surface of the berry while Cd penetrated into the interior of the fruit (MACK and BERG 1972, MACK 1975).

Metabolic effects of airborne toxicants

All plant species absorb SO_2 through the stomata of the leaf, and many can evolve both SO_2 and H_2S in the light. In darkness, only SO_2 is emitted. The H_2S that is evolved is derived from reduction of airborne SO_2 or endogenous SO_4^{2-}. Because the production of H_2S occurs in the light, it is believed to be related to reductive steps in photosynthesis. It may also be an important means of reductive metabolism of oxidized forms of S in the grape (DE CORMIS 1968, 1969, DE CORMIS and BONTE 1970).

Metabolic inhibitors, including F, were employed in physiological studies that compared *V. vinifera* cv. 'Bastardo' and 'Clare Riesling' (seeded) and 'Sultana' (= 'Thompson Seedless') and 'Black Monukka' (both seedless). Although treatment with F had significant impacts on many physiological parameters, there was little difference found between cultivars, whether seeded or seedless (HARRIS et al. 1971).

Germination of grape pollen and growth of pollen tubes were stimulated by treatment with the halogens, Cl_2, I_2, Br_2 (PORTYANKO et al. 1975).

Fluoride and monofluoroacetate were among 6 inhibitors tested on grape respiratory mechanisms. Monofluoroacetate clearly caused peduncle necrosis, decreased weight of berries, lower concentration of reducing sugars and K ions, and higher titratable acidity and Ca ions. By contrast, application of F discolored the berry skin, and decreased berry weight and sugar accumulation (WIENHAUS 1973).

Plant diseases

The relationship between the incidence and severity of plant pathogenic diseases on grape and air pollution was the subject of two investigations by MANNING (1971, 1975). In the vicinity of quarries and mills processing limestone, wild grape foliage with light to moderate deposits of dust had more fungal leaf spot lesions than leaves with heavy deposits. Dusty leaves were darker green in color but there was no effect on leaf size. The leaves also had a greatly increased population of phylloplane bacteria and fungi than clean leaves, but there were no qualitative differences. On grape leaves heavily encrusted with dust, *Streptomyces* spp. were absent, and the population and diversity of bacteria and fungi were reduced.

Protective applications

Ozone

In field experiments in 1967, 2 applications of N,N'-diphenyl-p-phenylenediamine (DPPD) resulted in an average increase in yield of 'Zinfandel' grapes of about 20 %, but variability precluded statistical comparisons. When repeated the following year, there were no differences and the authors suggested that unseasonal rains had removed the DPPD. In 1969, a group of vines received 3 spray treatments with 1.5 g 'active' DPPD applied per vine and formulated in a citrus storage wax emulsion. Where the emulsion dried in heavy deposits, the leaves were greener than surrounding tissue. Yield of berries was increased about 25 % and the result was statistically significant (THOMPSON and KATS 1970).

Somewhat later, the fungicide benomyl (methyl 1-butyl-carbamoyl-2-benzimidazole carbamate) was found to be effective in protecting many species of plants from oxidant stipple (TAYLOR 1970). When applied as a dilute foliar spray to 'Ives' and 'Concord' grapevines, oxidant stipple was reduced. 3—7 applications at 1.12, 3.36, and 6.72 kg ha^{-1} increased protection over unsprayed vines, but 1 or 2 applications were ineffective. The degree of protection afforded was directly related to the frequency of benomyl applications. In 'Concord', stipple symptoms were reduced to about 30 % of the foliage injured as compared with about 75 % injured in control vines (KENDER et al. 1973, KENDER and SHAULIS 1973, KENDER and MUSSELMAN 1976, MUSSELMAN 1980).

Over a 3-year period, ORMROD (1979 and undated) tested the effectiveness of chemical protectants to reduce or prevent oxidant stipple. Chlormequat, a growth retardant, generally increased leaf injury. EDU (N-[2-(2-oxo-1-imidazolidinyl)ethyl]-N'-phenylurea) an antiozonant, generally decreased the degree of stipple. When applied to 'Marechal Foch' and 'Agawam' vines, yield was increased without affecting fruit quality. In contrast to results of the research group at Geneva, NY, benomyl was found to be ineffective in the field trials. In controlled-environment studies, however, both benomyl and EDU were effective in reducing the severity of stipple.

Weekly applications of EDU were more effective than biweekly application in reducing the extent and degree of O_3 stipple. Soil applications were less effective. No fungicidal activity was found (MUSSELMAN, KENDER, HERTZBERG, and MELIOUS 1978).

Hydrogen fluoride

It has been known for many years (ALLMENDINGER et al. 1950) that the application of lime or other Ca-containing salts can protect plants from airborne F injury. Indeed, in some areas, it has been a standard practice to apply lime or other Ca-containing salts to protect peaches from the condition known as 'suture red spot'. It therefore comes as no surprise that Bordeaux mixture, a copper sulfate-lime fungicide, afforded nearly complete protection from airborne F injury to leaves of 'Semillon' (GREENHALGH and BROWN undated, 1982b; also cited in State Pollution Control Committee 1981). The protectant property of Bordeaux mixture to grapevines exposed to airborne F has been known for many years (HOPP 1966). Copper oxychloride has also been found to have some protectant properties against airborne F (GREENHALGH and BROWN, undated, 1982b).

Economic loss assessment

There have been only a limited number of papers that have evaluated the economics of yield loss of grapes from air pollution, due principally to the lack of proper data

bases. Only 2 researchers (FERRO 1960, POLELLI 1975, 1978) appear to have studied the effects of air pollution on economic losses to grapes. Both studies were conducted in Italy and injury was induced by industrial emissions of airborne SO_2 and F.

According to Article 1223 of the Civil Code in Italy, damage is defined as 'loss of earned income which occurs as a direct result' of exposure to an air pollutant (POLELLI 1978). The extent of damage to plants, including grapevines, from airborne F emitted from a glass factory was the basis for claims by farmers for indemnifaction. Leaves of grapevines were found to contain from 125 to 940 ppm F ($\mu g\ g^{-1}$, dry weight), depending upon the distance and direction from the source. A monetary value was assigned to vines that were destroyed according to the cultivar and the age of the vine, and hence lost productive capacity. The value of loss of berry yield was then determined based upon a fixed cost of 3000 Lire per 100 kilograms of fruit (FERRO 1960).

POLELLI's (1977, 1978) economic analysis of loss to grape production was based upon certain biological assumptions. One was that the average grapevine has an expected productive lifespan. A second was that foliar indices (degree of necrosis on 100 vines) can be assigned by the amount of foliar necrosis, and that this degree of injury can be related directly to expected longevity of the vine and seasonal yield loss. A third was that the foliar indices are the same for SO_2 and F. And, a fourth assumption was that all cultivars do not respond in the same manner to air pollutants. This method was used for purposes of arbitration and compensation for damage to vines at least until 1984 (WEINSTEIN, unpublished).

Conclusions

Considering the many problems encountered in grape culture in many regions of the world that have been attributed to airborne phytotoxicants, the research conducted both in quantity and quality, has been woefully inadequate. The relationships between air pollution and grape yield and quality, those characteristics of the fruit that are best related to wine production, are poorly understood. In the simplest and most direct experiments, such as those in which vines have been enclosed in chambers provided with filtered and nonfiltered air, differences in yield have been reported. These experiments are very useful in evaluating local effects that occur over one or more growing seasons and in specific regions. However, insufficient dose-response information is provided for use in the assessment of risk to a crop that may be grown under other variables associated with dose.

All too often, the authors provide no statistical analysis to support their conclusions, use inappropriate statistical analyses, or experimental designs that are too weak to stand statistical evaluation. In a few publications, one is left with the impression that the authors had predetermined the results before conducting the experiment or were perhaps too much impressed with the prevailing themes.

In order to leave the reader, especially one who does not specialize in atmospheric pollution, with some appreciation of the status of research in this area, the following opinions can be offered.

O z o n e

1. Losses in grape berry and vine growth, yield, and quality can occur in the field at ambient O_3 concentrations. This is especially true under prevailing conditions in southern California. Although effects may occur, little or no evidence has been forth-

coming to show that other components of the 'oxidant complex', such as peroxyacylni-trates, aldehydes, ethylene, etc., are associated with these losses, either alone or com-bined with O_3.

2. Some cultivars are extremely susceptible to O_3, while other exhibit remarkable tolerance. However, these observations have been associated with foliar lesions, and the relationship of the degree of susceptibility of foliage with fruit yield has not been established or even studied.

Sulfur dioxide

SO_2 alone at concentrations and durations of exposure not normally found or expected in the field, can cause reduced vine and fruit growth, yield, and quality, and premature defoliation of leaves.

Pollutant combinations

Research has been conducted only with O_3/SO_2. Reported effects are correlative with no credible cause-effect information. Even controlled exposures have not yet provided proof that these pollutants are interactive.

Hydrogen fluoride

1. Grape leaves, especially of some European cultivars *(V. vinifera)*, are very sus-ceptible to airborne gaseous F.

2. Grape foliage can absorb and accumulate high concentrations of airborne F, but translocation from leaf to fruit or direct uptake by the fruit from the atmosphere are not significant pathways. Grape foliage is not an exceptional accumulator of fluoride compared with many other species.

3. The rate of accumulation of F in foliage is not generally linear with time and concentration.

4. The relationship between accumulation of foliar F and the threshold for injury is best determined under field conditions.

5. The threshold concentration for foliar injury in the most susceptible cultivars appears to be 35—40 ppm.

6. The relationship between foliar injury and yield has not yet been established for any cultivar, although the open-field fumigations in western France are the best efforts to date.

7. Reduced yield may depend less on the presence and degree of foliar injury than on characteristics of exposure in one or more growing seasons and stage of vine development.

Heavy metals

1. No direct toxicity has been proven, but there is evidence of contamination in wines.

2. Although Pb is accumulated on the surface of the leaf or berry, Cd is present internally and could present a hazard even in washed fruits.

3. Some airborne compounds can alter the flavor of wines.

Air pollution problems exist in most important grape growing regions of the world, and the phytotoxicant ranges from primary sources, such as SO_2, HF, Pb, Cd, to secon-dary pollutants such as O_3, PANs, NO_x, ethylene, aldehydes, etc. Dose-response curves that can define and predict injury or yield or the nature of the effects produced have been left largely unstudied to date.

Abstract

A review of major investigations on the effects of air pollution on foliar symptoms, growth and development, yield and quality of fruits, and accumulation of airborne eco-toxicants in or on grapevines is presented. Because of the paucity and uneven quality of much of the peer-reviewed literature, many nonpeer-reviewed publications and reports have been included.

A number of serious and potentially serious air pollution problems in viticulture occur throughout the world and are associated with airborne fluorides, ozone, sulfur dioxide, nitrogen oxides, heavy metals, including lead and cadmium, and combinations of more than one pollutant.

Factors that control the response of grapevines to air pollutants, rates and sites of uptake and accumulation, and means of amelioration of their effects are among the subjects reviewed.

Acknowledgment

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